Global Temperature Stability by Rule Induction: An Interdisciplinary Bridge

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Abstract:
Rules incorporating influences on global temperature, an estimate of radiation balance, were induced from astronomical, geophysical, and anthropogenic variables. During periods of intermediate global temperatures (generally like the present century), the influences assume canceling roles; influences cancel the effects of extreme states potentially imposed by other influences because they are, in aggregate, most likely to be assuming opposite values. This imparts an overall stability to the global temperature. To achieve cold or hot global temperature, influences assume reinforcing roles. CO_2 is an active influence on global temperature. By virtue of its constancy in the atmosphere, it can be expected to sponsor frequent hot years in combination with the other influences as they cycle through their periods. If measures were implemented to maintain warm or cool global temperatures, it could retain the status quo of present global agricultural regions. They are probably more productive than hot world regions would be because of narrow storm tracks.
KEY WORDS: global climate; artificial intelligence; energy balance; rough sets.

Article:

INTRODUCTION

The articles in this issue discuss variations in the sources of energy that modify the earth's radiation budget. They are features of the earth's orbit, atmosphere, oceans, and geosphere that modulate the amount of energy admitted to, and retained within, the oceans and atmosphere. In this article we will examine the interaction of these influences within the modern atmosphere through annual global average temperature, an estimate of radiation budget. Because of the concern generated during the 1980s by numerous record high global temperature years, and questions about future change (Houghton et al., 1990), we direct our attention to the mechanism of global temperature stability.

The physical sciences have reasonably been concerned with the trendier aspects of global climate change. In the life sciences, occasional intimations of concern for interannual climate stability have begun to appear in the literature. Efforts to understand these life system effects can be expected to yield more easily to examination and explanation as year-by-year stability indices spanning thousands of years become more common. Thompson et al. (this issue) discuss the considerable range of information present in ice cores on global conditions. Through tree rings, Dean et al. (1985) provide a year-by-year index of regional climate stability in the southwestern United States spanning thousands of years. We make use of the worldwide and highly accurate measures of atmospheric temperature and related phenomena during the last decades to study temperature change processes. Close scrutiny of these data provides insights into the changes recorded in the long records. Results may apply across the sciences as historic and prehistoric climate records are drawn into the debate over anthropogenic contributions to global change. Rightly so, as the unforseen problems of global change, coupled with unrestrained population growth, have become the spectre of the 1990s.

Of first importance to the study of global climate stability is the theory that the average temperature of the atmosphere represents, or indexes, the status of the earth system including the atmosphere, oceans, and biota

(Budyko, 1977). It parallels the familiar belief that taking a person's temperature obtains a general understanding of his or her health. If the temperature is too high, it is interpreted to indicate infection or heat exhaustion. If too low, hypothermia or metabolic disorders are suspected.

For similar reasons, the status of the earth system can be measured by taking its atmospheric temperature. The temperature of the atmosphere is deeply involved with life processes. Were the temperature of the earth system not artificially maintained by the biota, distance from the sun dictates that it would be about —18°C (Budyko, 1977). For most forms of life, the annual temperature must average between 0° and 40°C. Current thinking suggests that the interaction of the global biota (Lovelock, 1979; Scientific American, September 1983) and global geophysical processes (Kasting et al., 1988) cooperate to regulate carbon dioxide and thus maintain the appropriate temperature. The biota sequester CO_2 in the ocean floors as limestone, and ocean floor plates recycle it to the atmosphere through subduction zone volcanoes. In the atmosphere, CO_2 modulates the thermodynamic system which, depending on the global average temperature, positions storm tracks that guide life-giving precipitation over the earth surface. For terrestrial life forms, atmospheric storm tracks are arteries that bring critical levels of moisture and temperature to regional habitats. As humans actively interfere in the sequestering of CO_2 through use of hydrocarbons for fuel, what threats do they pose to usual patterns of precipitation?

Three salient features of the atmosphere allow it to serve as an indicator of global health. First, it is ubiquitous. Second, it responds rapidly to changes in the energy inputs in about a month (Rampino and Self, 1984), as compared to longer response periods by oceans and biota. Third, atmospheric temperature is a part of the process that supplies moisture to life systems over the surface of the earth.

To analyze the atmospheric data, we turn to relatively new learning methods from artificial intelligence to examine the relationships between global average temperature and the aforementioned influences on global temperature and temperature stability. We will attempt to understand the climatic health of the world by observing the processes that regulate its temperature. This will be accomplished through a set of rules induced from the global temperature experience of the 33 years following the International Geophysical Year in 1957-1958.

RESEARCH DESIGN

Previous Research

The method we use is a form of artificial intelligence. A previous analysis utilized statistical methods to infer the magnitudes of influences on global temperature (Gunn, 1991). That research showed that the global average temperature between 1958 and 1987 may have been the outcome of astronomical, geophysical, and anthropogenic influences. A similar analysis performed for this article, but on updated data, indicates that 73% of movement in global average temperature between 1958 and 1990 was controlled by solar energy emissions, El Niño-Southern Oscillation, CO_2, and atmospheric transmission, an index of energy blocking in the upper atmosphere primarily by volcanic dust and soot from forest fires. The proportional contribution of each of these influences varied, with CO_2 Residual providing the greatest contribution and atmospheric transmission the least (Fig. 1).

Previous investigations of the effects of astronomical, geophysical, and anthropogenic influences on global temperature utilized various ap-

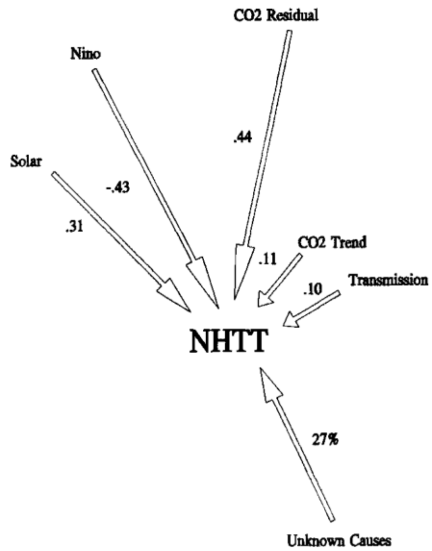

Fig. 1. Apportioning causes of global temperature (NHTT) by multiple regression (1958–1990). The values by the arrows indicate the relative contribution of each influence; CO_2 residual (.44) provides the greatest influence, atmospheric debris (.10) the least; the values are standardized regression coefficients. Twenty-seven percent of the Northern Hemisphere Tropospheric Temperature is not related to these influences and the sources of variation are either due to measurement error or remain to be discovered. The statistical significance of the linear regression equation is $p < .001$ (F-value of 14.8).

proaches. Bryson (1974) analyzed influences individually using thermodynamic calculations of the effects of each. Schneider and Mass (1975) and Gilliland (1982; see Shine et al., 1990 for a review of other similar efforts) calculated the proportional contributions of several variables. In addition to methods, our study differs from earlier research in that it is founded in highly accurate measurements over an extended period of decades. The analysis is explicitly multi-causal and accounts for simultaneous interactions among influencing variables.

Advantages of Rule Induction

Rule induction provides alternative analytical environment and assumptions. Especially useful are its nonlinear and qualitative properties. The previous statistical investigation examined global temperature measured by continuous or metric data. For rule induction, global temperature data are divided into discrete intervals, or states. Each state represents a module of information. Separation of the data values into states is informed by atmospheric theory. For rule induction, the states are joined to make rules.

There are at least three advantages to the rule induction approach:

1. The results of analysis by rule induction are essentially verbal descriptions of the causes of global temperature change. The familiar structure of syllogisms, if condition 1, and condition 2, etc., then conclusion, can be applied to the interpretation of the rules. The rules we generate read, if condition 1 is present, and condition 2 is present, etc., then a global temperature (in a specified) range will appear.

2. Although we will make use of underlying temperature trends to interpret results, rule-based analysis is not dependent on trends, even more so than existing nonlinear statistical methods such as

analysis of variance (ANOVA). States can occur in any possible order and relationships will still be detected in the rule generation process. This frees the analysis of the regression assumption that there are no step functions within the data. In fact, we make advantage of the apparent "jumps" in global temperature to define global temperature states.

3. The resulting global climate rules are compatible with rule-based expert systems (Grzymala-Busse, 1992). Such systems are capable of using many rules, even thousands. Because of this capability, they enjoy growing popularity in fields such as medicine and law where complex decisions are required on a routine basis. While we avoid evident small complexities of the combined astronomical-atmospheric-biotic-geospheric system to focus on the most powerful influences, larger rule sets could be managed handily in an expert system, thus making use of less potent rules to extend accuracy.

The philosophical issue engaged by both this method, and the previous regression and analysis of variance research, is one of single causes (mono-causality) vs. multiple causes (multi-causality), or apportioning of causes. The monocausal perspective constrains detection of causes to phenomena in single-cause and single-effect relationships. This perspective was commonly held earlier in the century when all science was thought of in essentially controlled laboratory terms. It was assumed that multiple causes could be reduced to single causes by laboratory controls.

For reasons that are obscure, this became the ideal of much of science, including the social sciences. Anthropologists, for example, fled to island societies to find controlled conditions. Since, the total interconnectedness of all elements of the earth's physical and biological systems have been generally recognized. Although largely abandoned in principle, monocausal concepts still invade much of the method and theory associated with disciplinary science.

Apportioned analysis assumes that all active variables contribute to an outcome, and thus causes must be measured by some means such as rough percentages (see Gunn, 1994). The apportioning perspective is one of the necessary methodological issues that needs to be addressed in order to realize analysis of systems of interconnected environments and organisms, sometimes referred to as landscapes; landscapes are the climatic, geological, biological, and cognitive context of human action (Crumley and Marquardt, 1987).

GLOBAL CLIMATE DATA

Global Climate Experience Since the IGY

Six measurements of the astronomical and earth system were used. The data comprise observations since the International Geophysical Year in 1957-1958. During the IGY consistent standards for accurate measurement of global temperature were implemented all over the world. Daily balloon releases through the atmosphere to approximately 100,000 feet altitude measure temperature along with other variables (Angell and Korshover, 1977). Along with other nations, the United States established a national climate observatory on Mauna Loa, an extinct volcano in the Hawaiian Islands, to measure CO^2 and many other properties of the atmosphere in an area apart from concentrated pollution (Keeling, 1978).

The data vary slightly from a previous analysis (Gunn, 1991). Three more years were added (1988-1990) increasing the global climate "experience" from 30 to 33 years. Also, a new variable was substituted to measure the amount of atmospheric transmission of energy to the surface. The discussion of these measurements will proceed by first examining global temperature. The global temperature is the dependent variable, or in the parlance of artificial intelligence, a "decision." There are five variables that influence global temperature. They are referred to as
tributes."

Decision

Global Temperature. Global average temperature, and consequent atmospheric circulation patterns, were represented by the average Northern Hemisphere troposphere temperature (NHTT) measured by daily balloon Hemisphere troposphere temperature (NHTT) measured by daily balloon releases. The data were derived from elevations between 850 mb (ca. 5000 ft) to 100 mb (ca. 30,000 ft). This is the main body of the lower atmosphere above most surface features and below the upper atmosphere or stratosphere. Values are deviations in degrees C from the 1958-1970 mean. A year is between December and November. Data were provided courtesy of J. K. Angell (1988). The lower atmosphere is used because the troposphere bears the air streams and moisture that affects surface conditions and life. It also appears to function as a separate system from the upper atmosphere that contains little moisture and is more dramatically disturbed by solar and volcanic events. The Northern Hemisphere is used because most of the related analysis of regional impacts of global climate change have been there. A similar analysis would be necessary using Southern Hemisphere data to implement regional change studies there.

Attributes

Solar. Solar energy output was coded as the international sunspot count for the period of study. Values are annual averages *(Solar Indices Bulletin).*

Transmission. Mauna Loa apparent transmission (Trans) data from the August 1991 *Climate Diagnostics Bulletin.* Apparent transmission is measured as the amount of sunlight reaching the surface through the atmosphere (Dutton et al., 1985). It is for the most part a measurement of the condition of the upper atmosphere indicating presence of volcanic debris and soot from large forest fires (see *Bulletin of the Global Volcanism Network,* various issues).

Niño. Values are winter average Southern Oscillation Index for December, January, and February from the *Climaté Diagnostics Bulletin* (March 1986 issue, Table 3A). Since 1986, data are from monthly issues. December is assigned to January and February of the following year. The index therefore leads the year and particularly the Northern Hemisphere growing season: this is important for measuring regional effects on biota. Negative values indicate an active El Niño. Though not representing all oceans, it does measure the status of the greatest source of the oceanic global temperature influences, the tropical Pacific (Rasmussen, 1985).

CO_2 Trend (CO_2T) and CO_2 Residual (CO_2R). Values are estimated regression values (Trend) and regression residuals (Residual) for July. Data are from Keeling, 1978 and NOAH since 1978. See Gunn (1991) for explanation of regression treatment of atmospheric CO_2. The CO_2 Trend probably reflects the growing anthropogenic contribution to atmospheric trace gases. CO_2 Residual represents lesser departures from the general upward trend. The residual variations seem to have both anthropogenic and earth system contributions. It appears, for example, to reflect reduced global use of hydrocarbons following the 1973 OPEC oil embargo. CO_2 serves as a surrogate variable for other trace gases which are also powerful greenhouse gases such as CFCs (Shine et al., 1990 review associated greenhouse gasses).

Theory of Global Climate States

To prepare the global climate data for analysis by rule induction, the continuous measures of influences and global temperature are converted to discrete values, or states. The first issue to be addressed, therefore, is whether there are theoretical bases for dividing the global temperature into finite states. Arguments that atmospheric temperature changes in uneven and irregular jumps have been offered. Bryson and colleagues (Wendland and Bryson, 1974; Bryson and Murray, 1977) have recognized for some time that, at the earth's surface, the effects of otherwise apparently smooth air streams, can change suddenly. This is due to both surface features and atmospheric processes. Surface features such as mountains, deserts, coasts, and warm pools of ocean water (Namias, 1970 Barry and Chorley, 1992, p. 111) can cause otherwise smooth flowing air streams to jump suddenly from one track to another. If atmospheric flows were unhampered by surface features, the average annual position of the jet stream would move smoothly from equator to pole as the global average temperature warmed (Webster, 1981). However, if the position of the jet stream encounters an obstacle such as the Rocky Mountains or Himalayan Plateau, it will remain south of the obstacle until a threshold of resistance is reached and then "jump" over it. Since precipitation is associated with the jet stream, agriculturalists (for example) who normally rely on the accompanying rains brought by the jet stream, will be affected by the movement to a new location.

There are potential causes of uneven changes in global temperature. At a given global temperature, the jet stream flows around the earth in a wave pattern composed of a given number of loops (Bryson and Murray, 1977; Barry and Chorley, 1992, see Rossby Waves). As the global temperature changes, only whole loops can be added to the wave pattern. Thus, the pattern resists change until a threshold is reached at which time a surface obstacle is transcended and another loop appears in the pattern. This process causes energy feedback to or loss by the atmosphere that is measured as irregular, non-gradual, step increases in the global temperature. From a specific location on the earth's surface, the addition of a loop is seen as a sudden radical change in climate as storm tracks shift to accompany the displaced jet stream.

Creating Global Climate States

A graph showing the distribution of global annual temperatures shows them to be irregularly spaced, as Bryson's theory suggests (Fig. 2). Both projects researching influences on global temperature (Gunn, 1991) and others defining the relationships between global temperature and regional hydrology (Gunn and Crumley, 1989; Gunn, 1992; Gunn et al., 1993) suggest that the average temperatures of the Northern Hemisphere can be

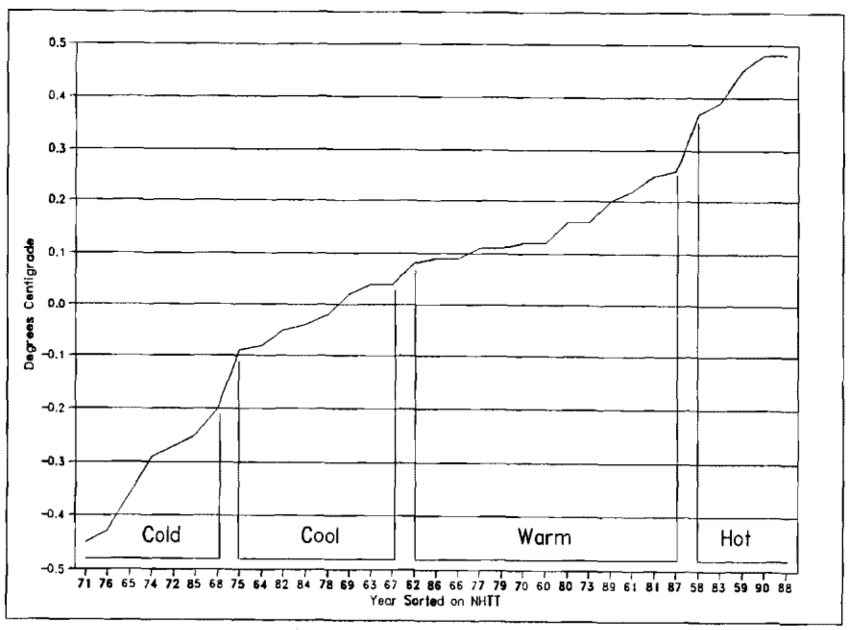

Fig. 2. Northern Hemisphere Tropospheric Temperature (1958–1990) showing global temperature states. Years constituting composited climates are shown along the bottom.

clustered into three or four states. These states can be taken to represent composited global climates; that is to say climates represented by several years whose common underlying feature is the similar status of the global average temperature (see Wigley et al., 1980; Gunn and Crumley, 1989; Gunn et al., 1993 for further discussion of composited climates). The four states are termed cold, cool, warm, and hot global climate (Table I). The composited climates are constituted of years between 1958 and 1990 of relatively similar global temperatures (Fig. 2, bottom Table I). The clusters are separated by breaks in the temperature distribution (Fig. 2, top).

The terms cold, cool, warm, and hot intuitively resemble very general global conditions by which climatologists, archaeologists, etc., characterize the changing climates of the Pleistocene (before 13,000 years before the present) ice age and the Holocene (after 13,000 years before the present in most parts of the world). "Cold" conjures images of Pleistocene ice age conditions and colder episodes of the Holocene little ice ages (see Denton and Karlen, 1973). Cool pertains to the less extreme cooler episodes of the Holocene. Hot world conditions were evidenced during the hottest episodes of the Holocene and may be experienced again from global warming. In the modem data, the 1980s were approaching a hot world condition. The hot cluster (n = 5) of years also contains years from the 1950s, another generally recognized period of global warming. The coldest cluster of years

Table I. States for the 1958 to 1990 Global Climate Data

	State	Range	Occurrences
Decision	Cold	−0.52–0.20	7
	Cool	−0.19–0.04	8
	Warm	0.05–0.29	13
	Hot	0.30–0.50	5
Attributes			
Solar	Lowest	10–67	15
	Low	67–91	3
	High	91–106	4
	Highest	106–185	11
Trans	Low	0.853–0.924	7
	High	0.924–0.935	26
Niño	On	−3.1–0.0	17
	Of	0.0–1.1	12
	Off	1.1–1.8	4
CO_2Residual	Low	−2.3–0.0	18
	Medium	0.0–0.4	2
	High	0.4–0.5	3
	Highest	0.5–2.8	10
CO_2Trend	Low	313.2–336.4	19
	High	336.4–352.3	14

(n = 7) probably approached the global temperatures during the Holocene little ice ages. The warm (n = 13) and cool (n = 8) cluster encompassed the range of most years between 1958 to 1990, and probably most non-extreme conditions for the Holocene.

The attributes are divided into states as well (see Table I). Creating attribute states involves grouping values into as few states as possible. At the same time, the influencing attribute states must retain the same ability to predict the global temperature as the original values. This was achieved for this analysis by clustering the attribute values using agglomerative cluster analysis. The use of rough sets (Pawlak, 1991) allows the states to interact freely during rule generation.

RULE INDUCTION

The LERS Approach to Rule Induction

The LERS (Learning from Examples based on Rough Sets) program utilized to generate the rules during this research is the descendent of several generations of artificial intelligence programs that learn from experience (Grzymala-Busse, 1992; p. 2, 1988). The genre of artificial intelligence implemented in LERS is a form of machine learning called similarity-based, or empirical, learning (Grzymala-Busse, 1992, p. 1). It is founded in induction of knowledge from empirical data. In this study, the experience, or training data, are the 33 years of observations following the International Geophysical Year (1957-1958). LERS operates on the states (as defined above) to form the rules. If we were diagnosing the condition of a human using similar principles, we would begin with "normal" and "fever" as health related states. We would know that approximately 98.6°F is the ideal body temperature. We might consider 100°F as a "mild" fever and 102°F, as a "severe" fever. Upon taking the patient's temperature, and, depending on how we interpreted the range of values read, we would find whether the person had fever or not. We would then induce something about the health of the individual based on the state of nonnormal fever, mild or severe.

In the context of our global analysis, there are suspected normal conditions as well, or at least normal for our lifetimes, and suspected abnormal conditions. Thus, our states of global climate will evolve around more normal conditions, a range of temperatures we conceptualized as warm or cool, and less normal conditions called cold or hot. During the decades of the study, two stand out as abnormal. The 1980s contained a series of years in which record high global temperatures were set almost annually. This global fever produced enough concern among scientists and the public to precipitate a close examination of global climate change. The 1970s were unusually cold, so that numbers of people moved to the "sunbelt" for no other reason than the climate.

The LERS program has a wide range of capabilities for analyzing data by different artificial intelligence approaches. The approach utilized depends on research objectives and the size of the dataset. A method thatdepends on research objectives and the size of the dataset. A method that generates a comprehensive, and therefore large rule system can be used on small datasets. However, as the data become more numerous, computational requirements rise and less demanding options are implemented that generate rules more selectively.

We experimented with options that minimized the number of rules by concentrating on the most powerful predictors of global temperature, even though our dataset was small. Seeking a small number of rules is a liability in terms of exhaustively and precisely defining all aspects of the system represented by the data. It, however, provides more interpretable rules. A more comprehensive analysis is presented in Grzymala-Busse andrules. A more comprehensive analysis is presented in Grzymala-Busse and Gunn (1993).

Two LERS program options were invoked to produce a minimal rule set. (1) The most powerful attributes in terms of their ability to define global climate states were given first priority in the rule making process. (2) Only the minimal subset of rules was used, as opposed to all possible rules. The minimal subset of rules is the smallest number of rules necessary to identify the global climates, given the attributes. The minimal subset of rules can be used in this example because the states of all attributes for all years are known. The identifications could be extended to other years (outside the experience) during which fewer attributes were known by using the list of all possible rules.

Rule Significance

LERS performs a test on the ability of the combinations of attribute states to identify decisions. Termed the leave-one-out test, it systematically leaves each year out, regenerates the rules with each year missing, and determines if it can identify the climate of the removed year. When all years have been so treated, and the correct identifications are divided by the total years, the result is a percentage estimate of the ability of the rules to identify decisions correctly on novel data. The leave-one-out test for correct identification of climates for this rule set resulted in accuracy equal to 42.4%. This could be improved with more rules. For now, we are concerned with broader principles detectable in global temperature processes and will leave concerns for narrower principles and improved accuracy for future research.

A second test measures the ability of each attribute to define states of the decision by itself. Ranked on this criterion, the LERS solution (Table II) showed CO_2 Residual to be the most important attribute as measured by the attribute significance test. This is the same finding as the regression significance order. Though locally inverted, solar energy and Niño appear in a similar order between the ANOVA and LERS analyses.

Clustering the values for the five attributes (see Table I) yielded four states for solar and CO_2 Residual, three for Niño, and two for CO_2 Trend and apparent transmission. Note that the greater the number of states in Table I, the greater the power of the attribute to individually identify climate states in Table II. The states were all given names to facilitate discussion of the rules. Table III shows the minimal set of the 22 certain rules that resulted from rule induction based on this configuration of states. The rules have been sorted on global climates from cold to hot to facilitate interpretation of attributes.

Principles of Rule Interpretation

In order to understand the atmospheric processes represented by the rules, we developed guidelines for interpreting them. Interpretation of rules utilizes three principles: trends, canceling roles, and reinforcing roles. The principles are used to group rules into subsets with the same global climate effects. Trends are attributes with similar order of states as global temperature; they are "correlated" in the usual statistical sense. For example, with only two exceptions (Table III, rules 4 and 19), CO_2 Residual states increase in magnitude with global temperature states. This implies that global temperature follows changes in CO_2. Transmission also tracks the trend of temperature with High transmission during hotter climates and Low transmission during colder climates. The clearer the atmosphere, the hotter the global temperature. Solar, Niño, and CO_2 Trend appear unordered relative

Table II. Rankings of Attributes by LERS and ANOVA

Rank	1	2	3	4	5
LERS; attribute significance	CO2Residual .455	Solar .576	Niño .636	CO2Trend .788	Trans .849
ANOVA: probability	CO2Residual .001	Niño .002	Solar .026	Trans .119	CO2Trend .943

Table III. LERS Rules with CO_2 Residual as Priority 5

Attributes					Decision	
Rule	CO2R	Solar	Niño	CO_2T	Trans	Climate
1	Low		Off			Cold
2	Low	Low				Cold
3	Low	Highest	Of	Low		Cold
5	Low	Lowest			Low	Cold
4	High		Of	High		Cold
6		Lowest	Of			Cool
7		Highest			Low	Cool
8	Low	High		High		Cool
9	Low	Highest	On	Low		Cool
13	Low	Lowest	Of			Cool
11	Medium			Low		Cool
10	Medium	Lowest				Cool
12	Highest		On	High		Cool
17		High	On	Low		Warm
15		Lowest	On		High	Warm
19	Low	Highest		High	High	Warm
18	Highest	Highest	Of			Warm
14	Highest	Lowest		Low		Warm
16	Highest		Off			Warm
21	Medium	Low				Hot
22	Highest	High				Hot
20	Highest	Highest	On			Hot
Count	18	17	12	9	4	22

to global temperature, so another principle applies to them, that of canceling roles.

In the cases of the non-trending attributes, solar, CO² Trend and Niño, *canceling* roles appear to explain their behavior *viz* the trending attributes. For example, rule 3 is a Cold climate rule, but it includes Highest solar energy. The association of highest solar energy emissions with cold global temperature seems incongruous. However, acting in canceling roles, canceling the warming effect of solar energy, are Low CO_2 Residual, Of status of Niño, (see Table 3) and Low CO² Trend. In short, an active sun does not by itself Hot climate make; rather to make hot climate it must, as in rule 20, be supported by elevated CO_2 and active Niño.

Reinforcing influences appear to offer the greatest insight into global climate stability. The number of rules required to define each of the global climates is revealing. The previous analyses of global climate indicated that the warm and cool global climate statuses are relatively stable and predictable conditions; the hot and cold global climates, on the other hand, are relatively unstable, though predictable, because they are caused by extreme states of influences (Gunn et al., 1993). Regression analysis results, however, offered no explanation of this stability. The same system of stability is present in the LERS rules, but with interpretability and explanations. The volatility of hot climate is intimated in that it is defined succinctly by only three simple rules (six attribute states). Cold climate requires five somewhat more complex rules (12 states). The intermediate warm and cool climates require larger and more complex rules sets, warm six rules (14 states) and cool eight rules (15 states). The explanation appears to be that hot and cold climates appear when more than one influence is in an extreme state and thus in reinforcing roles. If no more than one of the influences is in an extreme state, the global climate will hover persistently in an intermediate warm or cool condition because the other influences will probably (with a high probability) cancel it out. If we take the large number of rules to be indicative of a complex system (send Kaufman, 1993), it may suggest that earth systemic stability is possible through the interaction of a large number of influences. It is only when more than one of the influences is in an extreme state that global temperature moves significantly toward hot or cold.

Rule Interpretations

We now discuss the rules in groups, and attempt to gather insight from each group concerning the processes they govern in the global climate system. The complete rule groups for each global climate decision is displayed graphically in Figs. 3 and 4 to provide a comprehensive visual perspective on the LERS rules. The attributes are arranged according to causal order with solar energy emissions appearing from Lowest on the left, to Highest on the right. The rules are ordered on the solar energy emissions because it is the only truly independent source of change in the system. Abecause it is the only truly independent source of change in the system. A visual display was created so the size and complexity of the rule groups could be readily compared. The extreme states, hot and cold, appear in Fig. 3 and the intermediate states are in Fig. 4 to emphasize their mutually relevant roles. We will first discuss the extreme climates (items 1 and 2 below) and then the intermediate climates (items 3 and 4 below).

1. The rules governing Hot global climate involve, as would be anticipated, High (22) or Highest (20) solar energy emissions (see Fig. 3, top). High solar emissions are coupled with Niño On and Highest CO_2 Residual. These rules assume reinforcing roles to achieve Hot climate.

One rule does not conform to this logic of high causes and high effects. It suggests that Low solar energy and Medium CO_2 Residual (21)

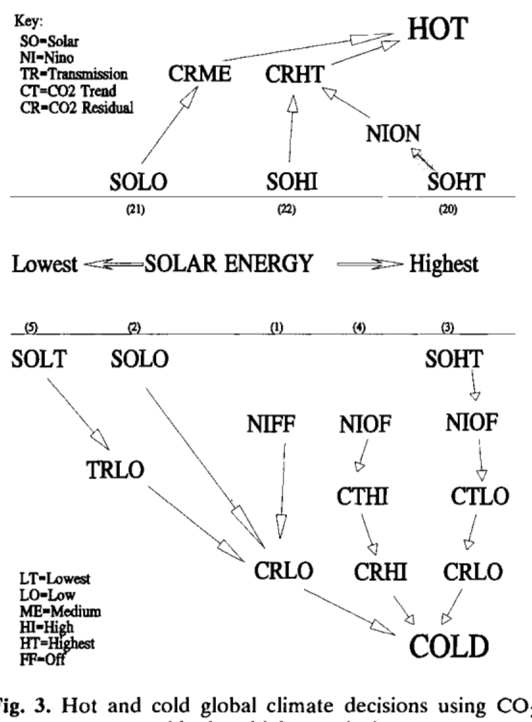

Fig. 3. Hot and cold global climate decisions using CO_2 residual as highest priority.

produce Hot climate. Examining the data, we find that the combination of states occurs only during 1983. This was the year following the largest volcanic eruption during the study period, and in fact the last 500 years, that of El Chichón during 1982 (see introduction to volume). It can be assumed of El Chichón during 1982 (see introduction to volume). It can be assumed that the apparently incongruous set of states formulating the rule were caused by an unusual and sudden decrease in atmospheric transmission due to an estimated 24,000 tons volcanic debris in the upper atmosphere. The reason for the apparently anomalous combination of states probably resides in the release of Niño energy associated with the eruption. This is frequently the case (see Handler and Andsager, this issue). The global climate remains Hot because the El Niño energy stands in for the blocked solar energy. It is an after-the-volcano rule: once the data are compiled for the 1990s it may appear again after the Mount Pinatubo eruption of 1991.

The after-the-volcano rule apparently represents the LERS's solution to a volcano-Niño statistical enigma. It has often been observed that vol-

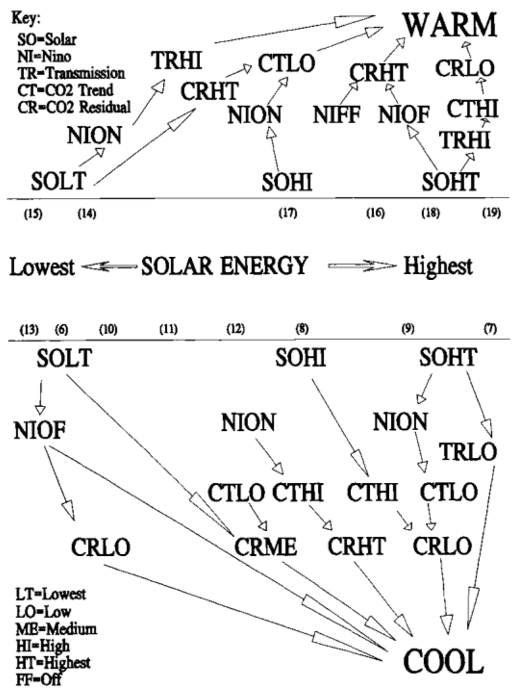

Fig. 4. Warm and cool global climate decisions with CO_2 residual as highest priority.

canic eruptions do not depress the global temperature as much as would be expected (Rampino, 1986). For statisticians, this is probably an intervening variable time series problem that needs to be resolved. Since major volcanic eruptions occur so infrequently, they as yet only figure in the statistical analysis of time series as lowered accounted for variance (r^2). LERS, on the other hand, manages the problem elegantly with a rule. It highlights the qualitative potential of the rule induction approach. This qualitative capacity allows LERS to identify a relationship whether it is a frequent or rare event.

2. The Cold global climate rules are most frequently simple cases of reinforcing states causing extreme conditions (see Fig. 3, bottom). They suggest that to achieve Cold climate, solar energy must be Low (2) or Lowest (5), transmission Low, Niño Off (1), and CO_2 Residual Low.

Two rules indicate canceling roles between CO_2 quantities and astronomical and geophysical conditions.

a) Cold climate may occur in the presence of High CO_2 quantities if Niño is Of (4).
b) Cold climate can occur during Highest solar energy output if Niño is Of, and both CO_2 quantities are Low (3).

3. The warm and cool global climate rules are much more complicated and reflect many more tangential conditions. They are, with only three exceptions out of 14 (rules 6, 12, 13), mixes of

high and low states, and thus are composed largely of canceling roles. Warm global climate can occur at almost any level of solar energy if the canceling conditions facilitate it (see Fig. 4, top).

a) Warm climate appears during Highest solar energy output if Niño is Off (18).
b) Warm conditions will appear in the presence of Highest solar energy, High transmission, and CO^2 Trend, if CO_2 residual is Low (19).
c) Warm climate accrues during High solar output while Niño is On, if CO_2 Trend is Low (17).
d) Warm climate can occur in the presence of Lowest solar energy if Niño is On, apparent transmission is High (15), or CO_2 Residual is Highest (14).

4. Cool climate appears through a welter of eight rules. Of the eight rules, five contain mutually canceling attribute states, and three contain reinforcing low attributes states. The canceling rules suggest that:

a) Highest solar output can allow cool climate if apparent transmission is Low (7)
b) Even with Niño On, Cool climate follows in the presence of low CO_2 quantities (9)
c) High solar energy and High CO_2 Trend can support Cool climate if CO_2 residual is Low (8).

The reinforcing rules are:

a) Lowest solar energy during Niño Of (6), and particularly when decremented by Low CO_2 Residual (13), produces Cool climate.
b) Without reinforcement of solar emissions, Niño On, in conjunction with High CO_2 quantities, can generate Cool climate (12).
c) Cool climate results from depressed CO_2 quantities (11).

In both the warm and cool rule groups there is association between canceling roles and large numbers of rules. This suggests that it is difficult to obtain warm or cool climate. However, they are the most frequent climates during the study period. This is an important topic of discussion for the conclusions.

CONCLUSIONS

In this analysis, we have experimented with small rules sets that may govern a large portion of the global temperature stability through astronomical, geophysical, and anthropogenic influences. There are two learning appetites that can be satisfied by investigating these influences in the context of the ongoing global experiment with environmental modification by humans. First, a scientific appetite is satisfied because it produces conditions that are highly variable and that have the potential to provide understanding of global climate change processes. The other appetite is that of policymakers. The research may answer questions about impacts on local climate as the global climate swings in response to the variations. How are humans to respond to the consequences of the experiment as governments and as individuals? Although the analysis of regional impacts will benefit directly from this work, it is dealt with in other papers (Crumley, 1994; Gunn and Crumley, 1991; Grzymala-Busse and Gunn, 1993).

Ordering results from theoretical and scientific, to practical and policy oriented, the rule induction findings can be summarized as follows.

1. Are there qualitative differences between the LERS approach and the more standard analysis of variance statistical approach that facilitates additional understanding of global climate? Like analysis of variance, interpretation of rules reveals with great clarity the mutually interactive character of influences on global temperature. Rule induction, however, adds dimensions to understanding of global climate change; it detects the change of attribute roles from canceling to reinforcing, an aspect of global climate that was not, and probably could not, be detected statistically. Statistics generally assume constant underlying processes.

There are also some very notable similarities between the LERS and ANOVA results. Both methods measured CO_2 Rresidual to be the most potent influence on global temperature. Niño and transmission are less important. We suggest that the subtle interactions of Niño and transmission, discussed by Handler and Andsager in this volume, tend to mask the individual influences of Niño and transmission. As mentioned above, the role that CO_2 Residual plays in the atmosphere is obscure. However, it may be a summation of at least the CO^2 Residual and Niño effects. As such it may be a simplified version of the two combined. This is an important research question. CO_2 Residual is an active player in both analyses. Does this indicate that in both methods the subtle interplay of Niño and transmission are masked? Are these combined influences revealed when viewed through the simplified measurements of CO_2 Residual?

2. The greater number of rules induced at intermediate global temperatures suggests inherent stability at intermediate global temperatures, and instability at extreme global temperatures. We suggest this is because intermediate states have the stable characteristics of complex systems. The extreme states appear to be unstable, reflecting the co-occurrence of extreme states in more than one of the influencing variables in a simple system.

3. The mechanism of stability-instability appears to be that roles vary through the continuum of global temperatures. During intermediate cool and warm climates, all or most of the influences assume canceling roles. Influences cancel the effects of extreme states in other influences by assuming opposite states. This imparts an overall stability to the global environment. The large number of nearly-equal players in the interactions assures that some influences will be canceling when another is an extreme state. During cold and hot climates, the relationships between the influences are generally reinforcing roles rather than canceling roles. That is to say that more than one must be in an extreme state — on or off, active or inactive — to create an extreme state in the global temperature. This creates globally unstable conditions that are highly responsive to changes in the influences.

4. Are there biocultural benefits to the stable global climate of the warm–cool regime? Other aspects of this project not reported here suggest there are. The chaotic behavior of weather systems during warm–cool global climate appears to foster more productive crops in at least one horticultural system, that of milpa, a climatically sensitive form of upland tropical gardening used in the Maya Lowlands of the Yucatan Peninsula (Gunn et al., 1993).

5. Perhaps the finding of greatest interest for policymakers is that the analysis does reveal an active influencing role for CO_2 (and trace gases). Non-normal global climates that usually only appear with astronomical and geophysical disturbances are reinforced by atmospheric trace gases. A previous analysis suggested that CO_2 couples solar energy emissions to ocean temperatures (Gunn, 1991; Cavadias, 1992). This may be all or part of the reinforcing process.

6. Are humans modifying the atmosphere in a manner that will produce meaningful changes in global climate for species survival, including their own? The very active role of CO_2 in the control of the global average temperature and climate suggested by this analysis indicates yes. Antecedent investigations to this one on the topic of the impact of global climate on regional climates indicate that mid-level global average temperature is advantageous to agriculture for a number of reasons (Gunn and Crumley, 1991; Gunn et al., 1993). Maintaining warm to cool global temperatures will maintain the status quo of present global agricultural regions. The warm—cool states of this century have provided relatively dispersed storm tracks, and thus generally wide, well-watered regions; exceptions have been hot decades such as the 1930s, 1950s, and 1980s. Archaeological evidence from the Medieval Optimum in North America and Europe appears to indicate that hot

climate concentrates storm tracks from along the subtropical jet (Arizona to the Great Lakes, see Bryson and Murray, 1977) and in Europe through southern Scandinavia. This would define narrow areas of flood, alternating with broad areas of drought. Most importantly, there would be little transition zone, or ecotone, between. Such a configuration of storm tracks worldwide could reduce temperate zone agricultural productivity.

This research suggests that as CO_2 achieves extreme states relative to the astronomical and geophysical influences, its effects will come to dominate the behavior of global climate. CO_2 will be a constant influence while all of the other influences are periodic by nature. Solar energy emissions follow an 11-year cycle, the El Niño a quasi-periodic 4-year cycle, and volcanism is also somewhat periodic in nature. The constancy of the CO_2 dictates that it will always be present as a reinforcing factor whenever the other influences rise to extreme states. In combination with the other influences, CO_2 has the potential to create strongly varying cycles in the global climate.

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